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STUDIES OF THE MARGINAL ICE ZONE ALONG THE EAST GREENLAND COAST

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Introduction

From the viewpoint of U. S. naval strategists, the Arctic Ocean has always been considered a potential warfare theater due to its contiguous boundary with the Soviet Union. Over the past several decades, however, naval operations in the Arctic have been quite limited and primarily of an investigatory nature to test and develop submarine operations under ice-covered waters. Recent advances in Soviet submarine-launched missile capabilities and their routine deployment on submarines operating in Arctic waters has brought an increased awareness to naval planners of the real potential for warfare in these waters. It is therefore prudent that studies be conducted of the hostile Arctic environment and its potential impact on naval operations, including platforms, weapons and sensors.

The study of polar oceanography has a long history at the Naval Postgraduate School (NPS) dating back to the mid 1960's when NPS faculty conducted sound speed and thermal microstructure studies from drifting ice camps in the Arctic Ocean.[1,2] Since the early 1970's, a course in polar oceanography has been offered at NPS, one of the few places in the U. S. to do so. This course was originally presented at the Naval Arctic Research Laboratory at Point Barrow, Alaska and was continued at Monterey only after closure of the Laboratory in 1979.

Beginning in 1971, NPS faculty have been involved in physical oceanographic studies of the marginal ice zones (MIZ) of the Pacific and Atlantic Arctic basins. To date, eleven ice-breaker cruises have been conducted in the ice-covered waters of the Chukchi, Beaufort, Bering and Greenland Seas during both summer and winter conditions. This research has been under the direction and sponsorship of the Arctic Submarine Laboratory, Naval Ocean Systems Center, San Diego, California. These studies have primarily been directed towards characterizing the water masses, currents, fronts, finestructure, and mesoscale eddies found in these dynamically active regions. NPS faculty were also actively involved in the international, multidisciplinary Marginal Ice Zone Experiment (MIZEX) sponsored by ONR and conducted in 1984 in Fram Strait off the east coast of Greenland. In recognition of this long-term commitment to Arctic research, the Chief of Naval Research established at NPS in 1977 a research Chair in Arctic Marine Science which today brings to NPS Arctic scientists of wide reknown and with widely varying areas of expertise.

In the sections that follow we have chosen to describe the results of our more recent efforts, namely the oceanographic characteristics of the East Greenland Current, rather than provide a broad overview of marginal ice zone oceanography. Many features of the MIZ are similar in both the Atlantic and Pacific, e. g., the association of a strong front with the ice edge. However, a hallmark of the MIZ is its extreme variability in both space and time. Hence, it is perhaps more instructive to restrict our description to a specific locale.

The remainder of the paper concerns discussions of the water masses, circulation and transport of the waters flowing over the East Greenland continental shelf and slope. Applications to naval operations are not explicitly addressed but are self evident, namely with regard to underwater acoustics and submarine operations under ice.

Oceanography of the EGC

The East Greenland Current (EGC) is the major outlet for Arctic Ocean surface water into the Atlantic Ocean and forms the western limb of the cyclonic gyre which occupies most of the Greenland Sea (Figure 1). It flows south over the East Greenland continental shelf. It's eastern boundary lies close to the shelf break where the current is concentrated into a high speed jet as a result of the strong topographically-generated oceanographic front, the East Greenland Polar Front (EGPF), formed there. This front separates the cold, ice-covered waters of Arctic origin to the west from the warmer, saltier North Atlantic-derived waters to the east.

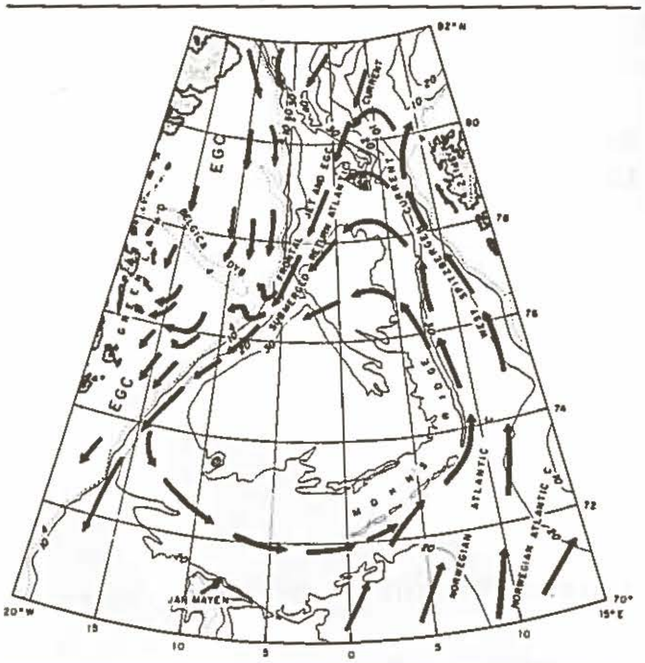
A comprehensive review of the characteristics of the EGC and its associated water masses was conducted by Aagaard and Coachman based on older data up to and including the 1964 and 1965 EDISTO expeditions. They identified three major water masses in the EGC whose names and properties have been slightly modified since then. Polar Water (PW), which extends from the surface to 150 to 200 m, is characterized by temperatures less than 0°C and salinities less than 34.5 ‰. A sharp thermohaline gradient separates PW from the underlying warm ($T > 0°C$) and salty (salinity maximum of 34.88 to 35.0 ‰) Atlantic Intermediate Water (AIW). AIW is itself a modified product of Atlantic Water (AW) ($T > 3°C$, $S > 34.9$ ‰; Swift and Aagaard brought into the region by the West Spitzbergen Current (WSC). Beneath the AIW, commencing at about 800 m. lies the nearly homogeneous Greenland Sea Deep Water (GSDW) having temperatures colder than 0°C and a limited salinity range of 34.87 to 34.95 ‰.

Warm salty water from the temperate regions of the North Atlantic flows into the Greenland Sea as the Norwegian Atlantic Current where a portion of it branches to form the West Spitzbergen Current. Some of this water, upon encountering the ice edge between 79°N and 80°N, sinks to intermediate depths of 200-500 m and enters the Arctic basin where it is traceable throughout as a warm ($T > 0°C$), salty layer. However, an uncertain but major portion of the WSC turns west, then south, to join with the EGC between latitudes 75°N to at least 82°N. This warm, southward flowing current, termed the Return Atlantic Current (RAC), is observed as both a surface and subsurface flow and forms the eastern boundary of the EGPF.

The near-surface water of the WSC is comprised of AW. As the WSC turns west and then south, the AW becomes cooler and slightly more dilute due to interaction with the ice edge. Hence, the waters which comprise most of the RAC are predominantly of the type AIW. In summer some AW may be present in the core of the RAC, especially at latitudes above 77°N.

Figure 1

Bathymetry (meters x 100) and currents in the Greenland Sea derived from a variety of sources (from Paquette et al., 1985). Fram Strait separates Greenland and Spitsbergen.



Recent Observations in the East Greenland Current

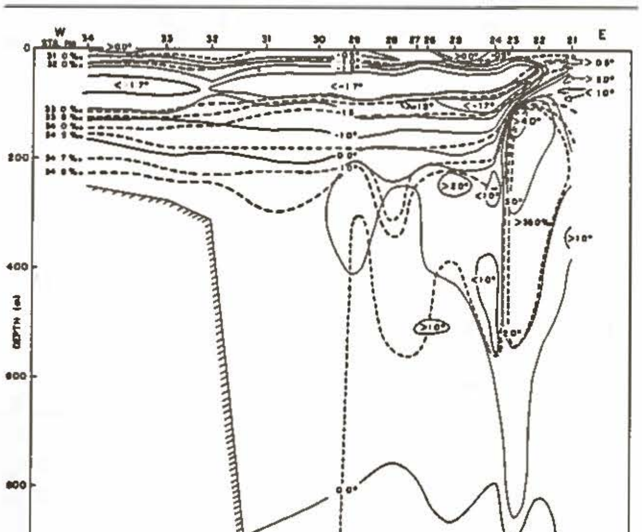
Commencing in 1981 the Polar Oceanography Group at NPS conducted several extensive surveys of the East Greenland Current (EGC) from the ice breaker NORTHWIND. The NORTHWIND surveys were conducted in October-November 1981 and August-September 1984 and 1985 and included the region between 75°N and 82°N. The NORTHWIND 81 cruise provided the first detailed observations of the temperature and salinity properties and baroclinic flow characteristics of the EGC.[6,7] Transects across the front, constructed from closely spaced oceanographic stations, illustrate frontal conditions at the onset of freezing. A much more extensive set of cross-sections were obtained during the summer of 1984 which demonstrated both seasonal and interannual changes.[8,9]

Frontal Features

Two vertical cross-sections of temperature and salinity from September 1984 are introduced to describe some of the features of the EGPF and to also highlight some of the features described above. The crossing along 79°55′N (Figure 2) indicates that the front (observed by the near-vertical slope of the isotherms and isohalines) is positioned in deep water more than 100 km east of the continental slope. The front is closely aligned with the ice edge which at this latitude trends northeastward toward the north coast of Svalbard. Farther to the south the front and, as will be seen, the high speed jet of the EGC converge onto the shelf break near 79°N remaining aligned with it at least as far south as 73°N.[4] A transect along 78°10′N (Figure 3) illustrates this alignment with the continental slope and also shows that warm AIW overlies the shelf, e.g., compare the positions of the 1°C isotherms in Figures 2 and 3. The latitude at which the EGPF converges onto the shelf break varies both seasonally and annually in response to the position of the ice edge but generally is constrained between 78°N and 79°N. This variability is closely coupled with the volume flow rate and heat flux variations experienced by the WSC. For example, the ice edge across Fram Strait melts back to higher latitudes during periods of greater warmth and flow rate.

Figure 2

Temperature (solid line) and salinity (dashed line) transect along 79°55′N. The East Greenland Polar Front, observed by the near-vertical slope of the isotherms and isohalines, is displaced about 120 km east of the continental shelf break. The Return Atlantic Current is identified by the core of water warmer than 3°C.



In both these transects, a warm (> 3°C) core of RAC is observed nestled close to the front causing the temperature gradient to be strongest there. The core has frequently been observed to be separated into horizontal and vertical filaments; their north-south length scales have not been well defined. The temperature-salinity characteristics of the core waters apparently vary with latitude both decreasing slowly with decreasing latitude due to continuous mixing with PW along the frontal boundary.

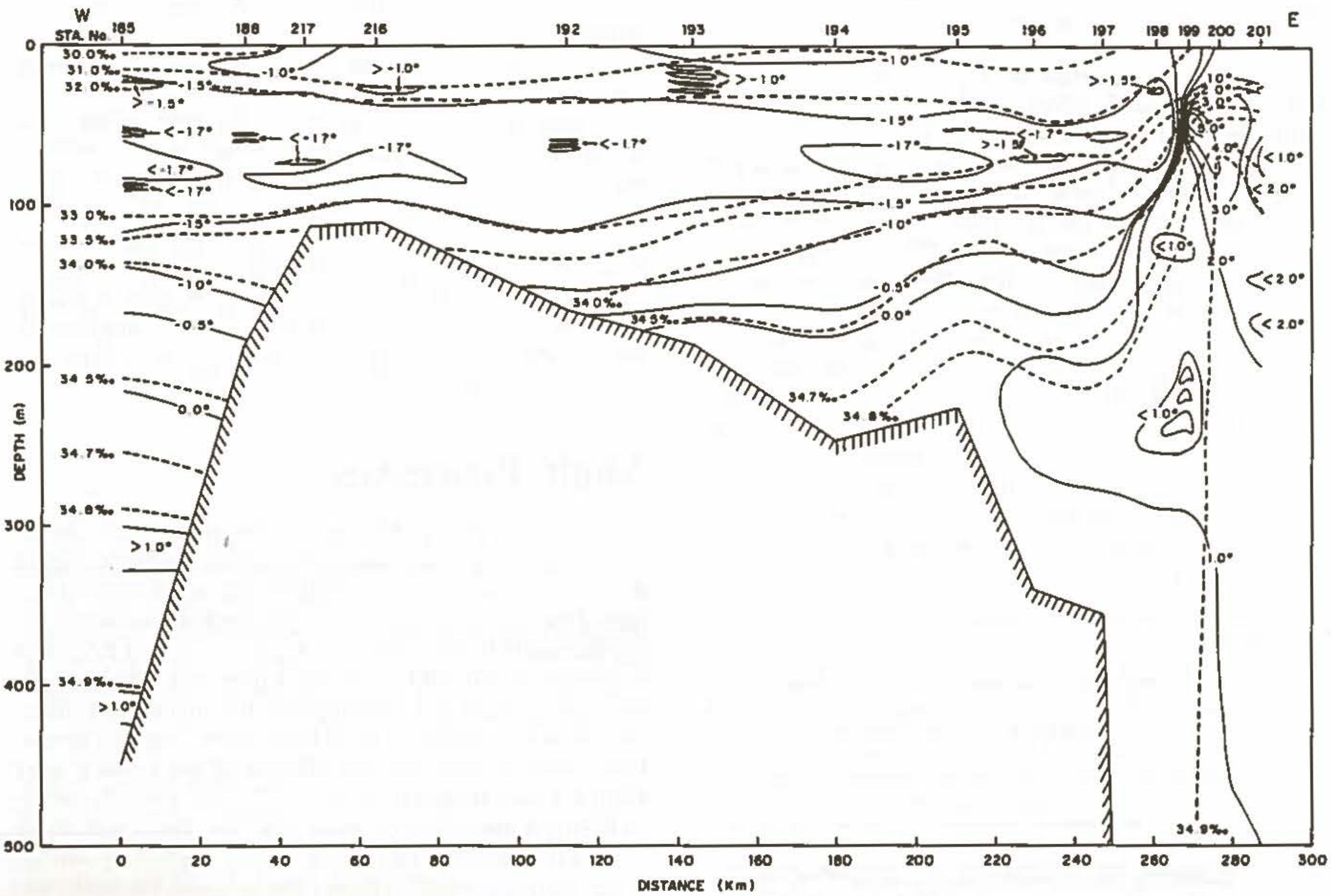
Based on the trend of the 0°C isotherm the mean slope to the EGPF is approximately 4 m/km in summer,[8] becoming two or three times steeper in winter.[6] North of about 77°30′N, the front is often separated into an upper and a lower portion. The extension of the upper frontal boundary to the east is probably often due to the formation of an extensive cold surface layer by the melting of nearby ice. Southward, where the RAC flows parallel and beneath the ice edge, less melting occurs and the front is generally continuous to the surface.

Shelf Processes

The bathymetry of the East Greenland shelf is marked by a series of banks and interconnected troughs (Figure 4) which influence the circulation and water mass structure of the overlying waters. The predominant water overlying the shelf is PW which in Figure 3 is seen to extend to depths of 150-200 m. In the winter this water is near the freezing point and, due to convective mixing and advection, may be isothermal to 50 m or more. Summer insolation causes a warming and dilution of the surface layer from a winter temperature of −1.7°C and a winter salinity having a maximum of about 33.8 ‰. These effects are visible In Figures 2 and 3. The lens of cold (< − 1.5°C) water centered near 50 m in Figure 3 is of particular interest in that it is a residuum of water brought to the freezing temperature during the preceding winter. This water has been little modified since winter and thus indicates that vertical mixing of heat and salt is near zero in that depth zone. The layer is of lower salinity than waters of similar temperature but located near the EGPF. In 1984 much of this water was constrained between a narrow salinity band of 32.1 to 32.5 ‰ while in 1979 it was found In the salinity range 33.2 to 33.4 ‰. This difference appears to be a result of the qreater freezing stress experienced in 1979, i.e., the number of freezing degree days was substantially greater in 1979 than in 1984 resulting in more ice formation and increased brine production. A comparison of shelf PW with PW from the Arctic basin or farther east in deep water indicates that the PW over the shelf is modified by coastal and local processes leading to substantial dilution.

Figure 3

Temperature and salinity transect along 78°10'N. At this latitude and farther southward the EGPF is aligned with the upper continental slope. Warm AIW overlies much of the shelf.



Beneath the PW is AIW which covers the deeper parts of the shelf region westward to the Greenland coast. In shallow areas, such as Belgica Bank seen near Stations 216 and 217 in Figure 3, the bottom shoals into the PW essentially eliminating all the AIW in these shallow areas. Overlying the shelf break and upper continental slope, many of our transects have shown that warm patches of AIW (temperatures > 1°C) are present. In Figure 3 such a patch appears to be forming. These occur sporadically in time and space and their generation mechanism has not yet been identified.

The troughs which cut across the Greenland shelf act as channels permitting the warm, salty AIW to penetrate far back onto the shelf extending its influence on shelf processes much more than otherwise possible. Water warmer than 1°C and saltier than 34.9 ‰ can be seen along the entire length of Belgica Trough (Figure 5) extending to the southern reaches of Norske Trough (Figure 3). The bottom waters of Westwind Trough are not as warm (< 0.5°C) since, as previously noted, at the latitude of its mouth the EGPF is more than 100 km seaward, effectively diminishing much of the warm source waters.

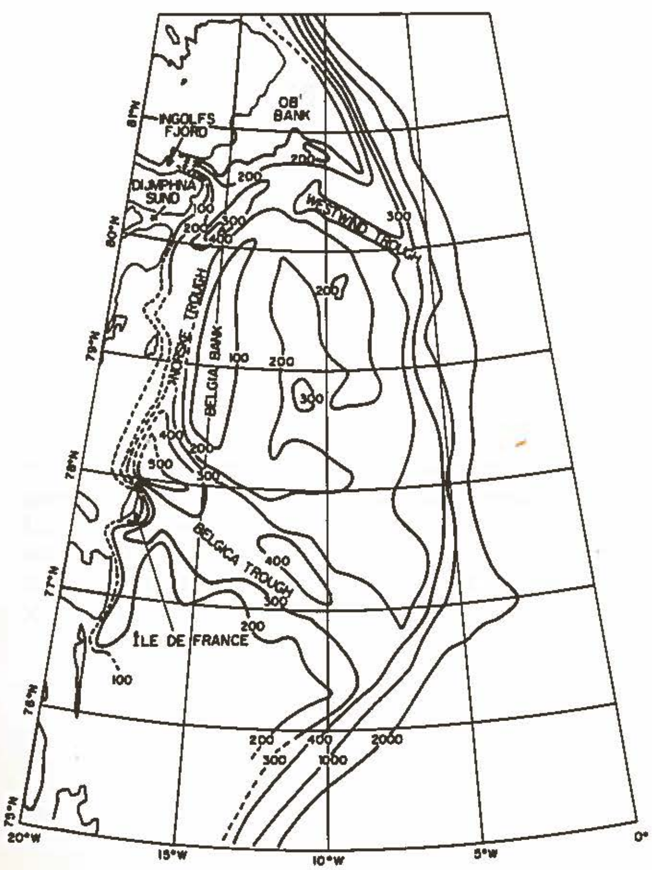
Finestructure

Finestructure, the temperature inversions resulting from interleaving of AIW and PW, generally is restricted to areas immediately to the east of the EGPF and in the upper 300 m. Compared to the early winter 1981 data, the finestructure observed in 1984 was weak and not widely distributed. An example from 1981 is shown in Figure 6. Finestructure of this nature is presumed to be formed by cooling of AIW at or near the surface east of the EGPF and descending westward along isopycnals into the frontal region. The finestructure lenses are markedly filamented in both the cross- and along-frontal directions with maximum estimated along-front length scales of approximately 30 km.[7] The effect of the ship's drifting in and out of these lenses is observed in Figure 6 where a large intrusion centered near 275 m is present in the upward traverse of the CTD but is totally absent in the downward traverse taken some 20 min. earlier.

The effect of these finestructure lenses on low-frequency acoustic propagation was examined by Sleichter.[10] Using a range-dependent transmission-loss model, he found that the presence of finestructure served to increase the overall complexity of the transmission loss curve causing target signals to fade in and out in response to the multipath, interference patterns.

Figure 4

Bathymetry (in meters) of the northeast continental shelf of Greenland (from Tunnicliffe, 1985). A series of shallow banks and interconnected troughs influences the circulation and water mass structure of the overlying waters.



Circulation and Transport

The circulation over the East Greenland shelf is dominated by a narrow, swift-moving flow associated with the EGPF and an anticyclonic rotation centered on Belgica Bank (Figure 7). The latter is a near-surface baroclinic (density driven) flow extending to about 150 m, the approximate boundary between PW and AIW. The northward flow along the coast has been substantiated by ice drift measurements using NOAA-7 imagery.[8]

Vertical velocity sections across the EGPF and shelf illustrate the nature of the flow of the EGC. A section along 77.5°N (Figure 8) shows the limited horizontal and vertical extent of the frontal jet, 50 km and 100 m, respectively. In 1984, maximum southward baroclinic speeds of 0.12 m/s to 0.67 m/s were computed. In early winter 1981, when the frontal gradient was even sharper, maximum southward speeds of 0.80 m/s to 0.96 m/s were obtained. Farther west over the shelf current speeds are much reduced, of the order of 0.05 m/s to 0.1 m/s. Near the Greenland coast a northward flow of up to 0.12 m/s was encountered.

Recent current-meter measurements taken during the MIZEX 1984 experiment by Muench[11] at 100 m and 400 m depth indicate the vertical shear is about the same as indicated in Figure 8 but that the current speed at these depths is approximately twice as fast, suggesting that the additional flow due to the slope of the sea surface is not negligible. A mean southerly baroclinic transport, across both the shelf and the front, of 1.47 Sv (10^6 m^3/s) was determined. Considering the northward coastal flow of 0.58 Sv, the net flow of the EGC in 1984 was 0.89 Sv southward.

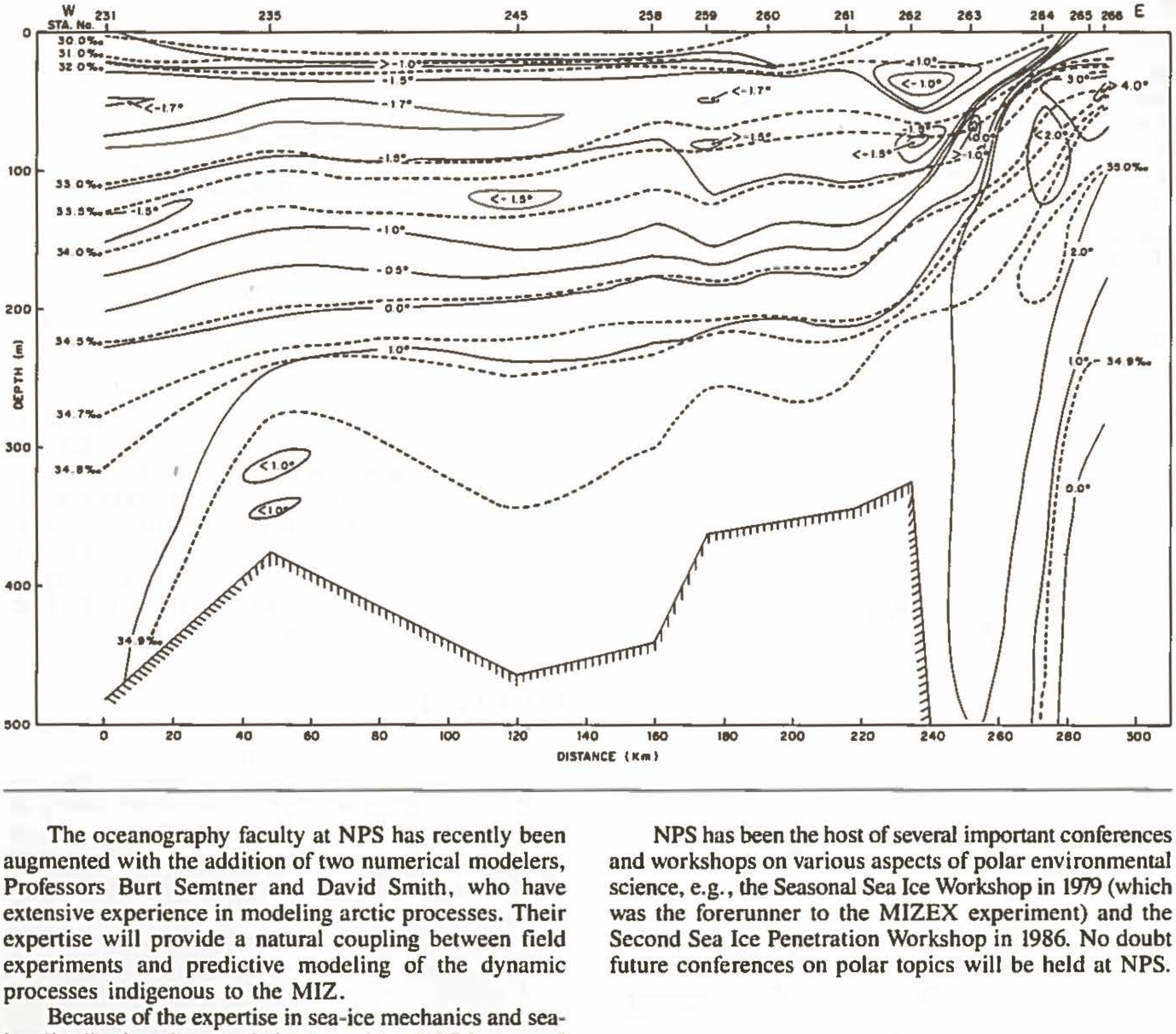
Future Plans

Future research cruises to the MIZ are planned on a nearly annual basis. During the summer of 1986, we conducted a bathymetric and oceanographic survey of northern Baffin Bay and Nares Strait. We also plan on expanding our instrumentation suit to include the ability to make current-meter observations using both moored arrays and expendable probes. The moored arrays are expected to provide long-term observations, remaining in place for about a year.

In order to more fully assess the impact of the complex MIZ environment on acoustic propagation, we are obtaining a series of drifting buoys which will not only measure standard atmospheric parameters but oceanographic and acoustic ones as well. The buoys will be equipped with a thermistor chain and two or more hydrophones. Our plan is to make ambient noise and transmission loss measurements in the MIZ and develop predictive models which will simulate the measurements.

Figure 5

Temperature and salinity transect along the axis of Belgica Trough. AIW warmer than 1°C extends far back on the shelf eventually flowing into Norske Trough near Station 231.



The oceanography faculty at NPS has recently been augmented with the addition of two numerical modelers, Professors Burt Semtner and David Smith, who have extensive experience in modeling arctic processes. Their expertise will provide a natural coupling between field experiments and predictive modeling of the dynamic processes indigenous to the MIZ.

Because of the expertise in sea-ice mechanics and sea-ice distribution characteristics brought to NPS by several former Arctic Chair incumbents, an ongoing research program has been developed in this area. The primary emphasis is to establish the spatial and temporal distribution of sea-ice thickness, an important factor in ice-penetration studies.

NPS has been the host of several important conferences and workshops on various aspects of polar environmental science, e.g., the Seasonal Sea Ice Workshop in 1979 (which was the forerunner to the MIZEX experiment) and the Second Sea Ice Penetration Workshop in 1986. No doubt future conferences on polar topics will be held at NPS.

Figure 6

Temperature and salinity profiles (both up and down traverses are shown) from a 1984 frontal station which demonstrate the large temperature inversions or finestructure indicative of interleaving of cold, fresh Polar Water with warmer, saltier AIW (from Paquette et al., 1985).

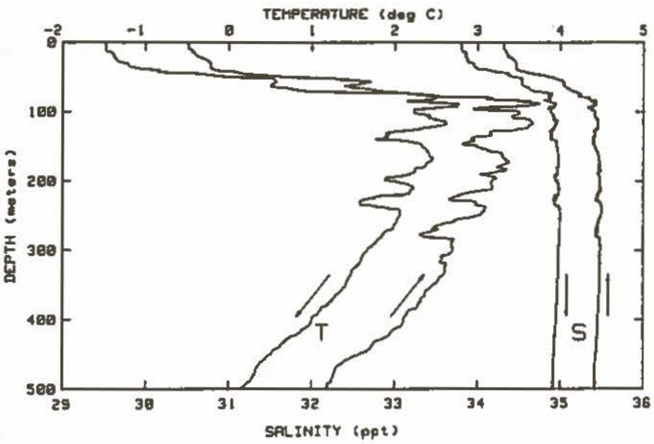


Figure 7

Pictoral representation of the near-surface density-driven (baroclinic) circulation over the East Greenland continental shelf. The length of the arrows is suggestive of the relative speed with maximum speeds near the EGPF (from Tunnicliffe, 1985).

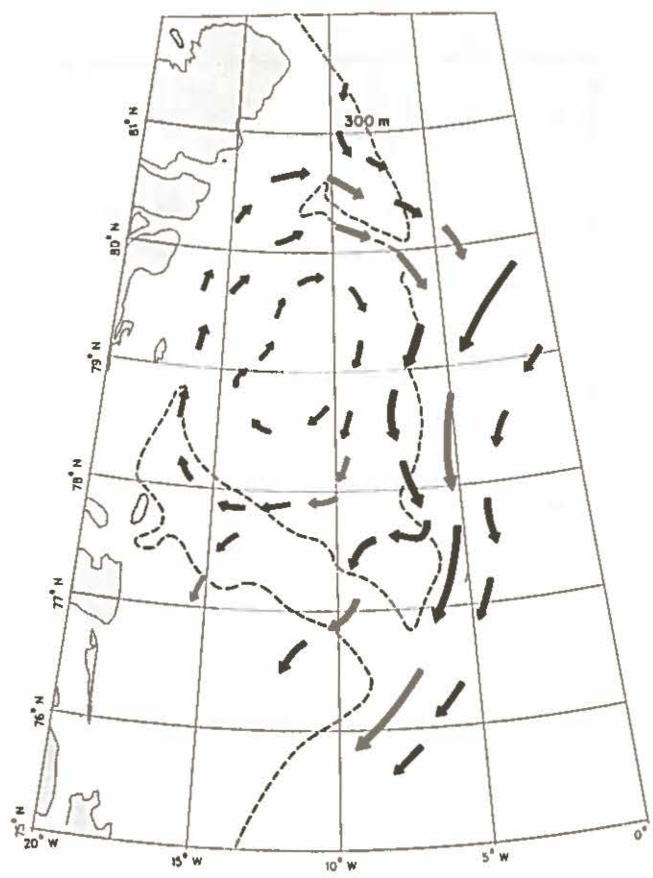
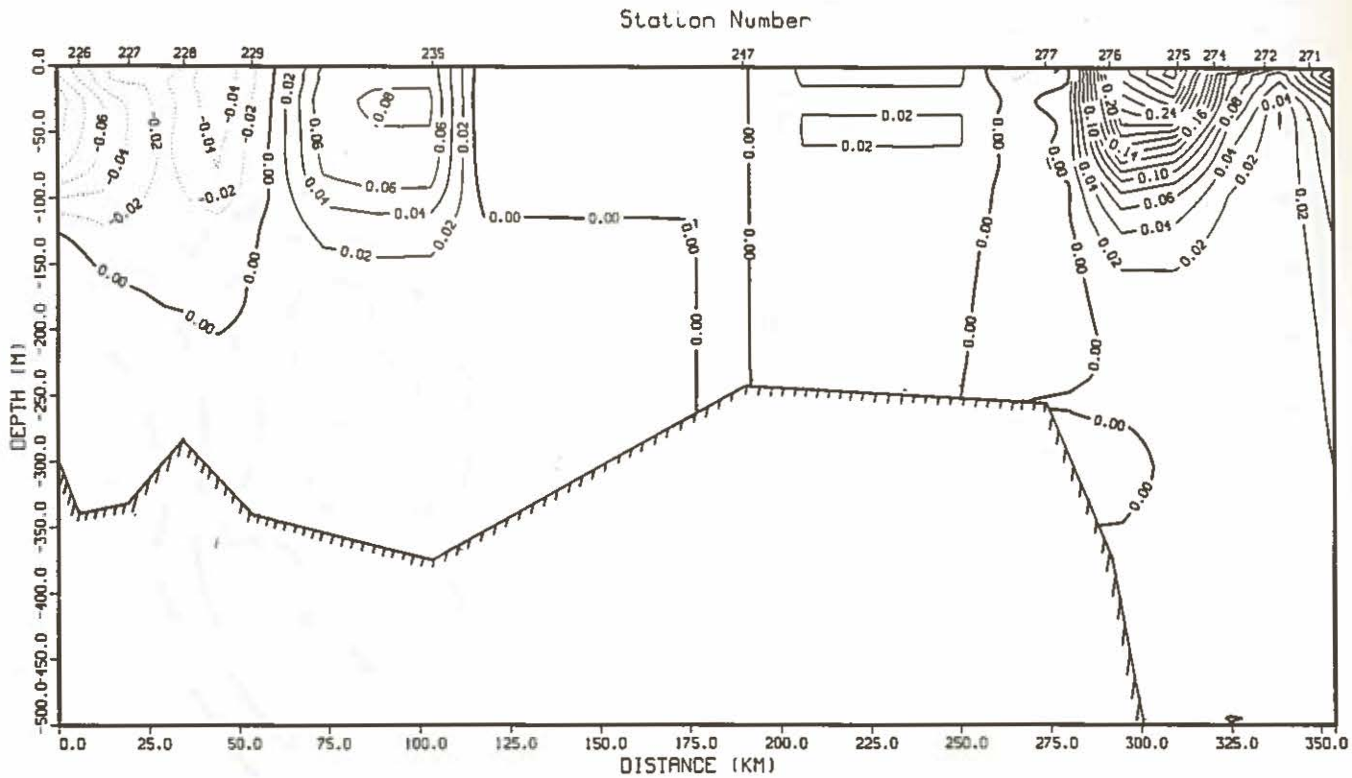


Figure 8

Vertical baroclinic current velocity section along 77.5°N (contours in m/s). The jet of the EGPF indicates speeds of up to 0.34 m/s. Northward flow (dotted lines) of 0.1 m/s over Norske Trough is seen near Stations 226 and 227.



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Biographies

Professor Robert H. Bourke heads up the Polar Oceanography Group at the Naval Postgraduate School. He has made eleven ice breaker cruises to the Pacific and Atlantic marginal ice zones during the past 15 years. In addition to conducting polar research, he is also active in the field of environmental acoustics.

Emeritus Professor Robert G. Paquette has a long history of polar research having participated in cruises to the Arctic Ocean in 1951 and 1952 as well as during the decade of the 1970's. Although now retired, he continues to be active in data reduction and analysis efforts.

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Growth and motion of vortices generated by a plate at an angle of attack of 60 degrees. The picture is taken in a recirculating water table and the vortices are visualized by means of aluminum dust. The alternate shedding of vortices takes place practically about all bluff bodies (cylinders, cables, missiles, etc.) and gives rise to large drag, oscillating lift force, and hydro- or aero-elastic oscillations. The flow field may be simulated numerically through the use of the fundamental equations of motion. The visualization of flow helps to our physical understanding of the phenomenon and provides data for comparison with those obtained in numerical experiments. (See article beginning on page 3.)

Photograph is the courtesy of Professor Turgut Sarpkaya (NPS).

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